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FINAL REPORT

to the

Office of Naval Research
(Attn: Dr. Andre M. van Tilborg)

on

**PRECISION ACTUATOR SYSTEMS RESEARCH
AT THE UNIVERSITY OF TOKYO**

(Host: Prof. Toshiro Higuchi)
Department of Precision Machinery Engineering
Faculty of Engineering
University of Tokyo

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ABSTRACT

This report summarizes the outcome of the visit to the University of Tokyo and the Kanagawa Academy of Science and Technology (KAST). The visit was part of the Foreign Science Analysis program sponsored by the Office of Naval Research, and its duration was from May 24 to June 26, 1993. The purpose of the visit was to observe and analyse the mechatronics research effort headed by the host professor, Prof. Toshiro Higuchi of the Dept. of Precision Machinery Engineering, who has a joint appointment at the KAST. In particular, the report covers four main topics; magnetic levitation, impact drive system, electrostatic film actuator, and ultrasonic motor. Research on each of these areas is being actively carried out at the University of Tokyo and the KAST. The research effort at the KAST is coined as the 'Ultimate Mechatronics', and there is a strong industrial participation in terms of financial support as well as technology transfer.

I. INTRODUCTION

Mechatronics is a research area being actively pursued by the Japanese. While it is an impossible task to try to summarize all aspects of the research being carried out in this area in Japan, it is hoped that the following summary on the research activities headed by Prof. Higuchi provides an insight into the depth and the quality of mechatronics research activities in Japan.

It has been perceived that the bottleneck of mechatronics is the lack of mechanisms which can implement advanced control schemes with sufficient accuracy and performance. Conventional mechanical structures suffer from friction and backlash to the degree that the advanced control is merely an impractical proposition. This is especially true in precision mechatronics where the size of the structures ranges from 1 μm to 10 mm, at which friction rather than inertia takes a dominance. Prof. Higuchi's effort in the past ten years has been that of a mission to eliminate this bottleneck. Development of new devices summarized in this report is born out of this very mission and attests to his paramount contribution to the advancement of mechatronics field.

It should be pointed out that the sheer amount of research activities headed by Prof. Higuchi goes well beyond what this brief summary entails. Based on the author's interest and the fields of expertise, four areas of research were chosen and studied in depth for the purpose of this report. The first area, magnetic levitation, is described in Section II. Effort in this area includes what has been coined by Prof. Higuchi himself as the Magnetic Servo Levitation (MSL), magnetic suspension using permanent magnets, and magnetic suspension using tuned LC circuit. Section III describes the work pursued by Prof. Kurosawa, who recently joined the Higuchi Lab of the University of Tokyo as an Associate Professor. He is a world expert in the field of ultrasonic motors that utilize piezoelectric elements. These two sections summarize the efforts pursued at the University of Tokyo, Department of Precision Machinery Engineering.

Section IV is devoted to the efforts pursued at the KAST by Prof. Higuchi. Firstly, a new micromotion positioning device actuated by electrostatic force is discussed. The most prominent feature of this 'film actuator', so named after its shape, is the power-to-weight ratio comparable to human muscle. An immediate application of such devices in industrial robot design is being actively carried out at the moment. Secondly, the Impact Drive System (IDS) which makes use of certain features of Piezo-electric (PZT) materials to realize accurate nanometer positioning capability is discussed in this section. Finally, in Section V, some afterthoughts and general comments about the program are offered.

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II. MAGNETIC LEVITATION

Magnetic levitation provides an ideal means of suspending mechanical systems because of its friction-free, backlash-free, wear-free and lubrication-free nature. Its applications have been found in magnetic bearings, magnetically levitated vehicles, and others. Also, its potential usage in special environments such as vacuum, clean room, and space are being actively studied.

In large, there are two types of magnetic levitation, possessing passive and active characteristics, the main difference being that the latter requires position sensors for closed-loop control. For the passive case, the levitating force can be classified into repulsive force of permanent magnets (Yonnet, 1978), edge-effect restoring force (Sabnis, 1974), resonance-effect restoring force (Kaplan and Regev, 1976), induction repulsive force (Eastham and Rodeger, 1984), and Meissner-effect restoring force (Buchhold, 1960).

Active magnetic levitation utilizes the attractive force of electromagnets. Let's refer to Figure 1 for a simple model of one degree-of-freedom (DOF) active magnetic levitation. The gravity pulls the object down while the attractive force produced by the two electromagnets attracts the object in the upward direction. If the coil current of the electromagnets is constant, the levitation becomes unstable eventually. To stabilize it, the gap between the object and the magnet has to be sensed and the coil current has to be 'actively controlled' to maintain a certain air gap length. Much research has been done on this regulation problem to stabilize the levitation (Chikada and Furuta, 1979; Ulbrich, Schweizer, and Bausar, 1979; and Mizuno and Higuchi, 1984).

At the Higuchi Lab of the University of Tokyo, three different approaches to active magnetic levitation have been developed, which are summarized in this section.

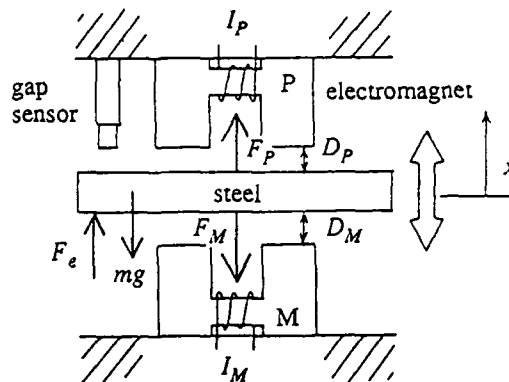


Figure 1. Magnetic Servo Levitation of 1 DOF

A. Magnetic Servo Levitation (MSL)

Recently, there have been a number of applications of MSL developed including Salcudean and Hollis (1988), Iwaki and Matsuda (1988), and Shingu (1990). However, the work by Tsuda and Higuchi (1992) is the most comprehensive and arguably the only

work that lays the fundamental ground work for a general analysis or synthesis of MSL devices.

What is MSL

A distinction should be made between conventional active magnetic levitation and magnetic servo levitation (MSL). Referring to Figure 1, again, a conventional active levitation is designed to regulate the position of the object at a fixed point. In MSL, the position of the object is varied along the vertical direction by changing the levitation force. Also, by virtue of the fact that the force can be changed by controlling the coil current in the windings, the force acting on the object can be precisely controlled as well, provided the current-to-force relationship in the electromagnet is accurately modelled. It is this force/position control capability that distinguishes MSL from conventional active regulating levitation.

To bring about such capabilities, certain shortcomings which are inherent to active magnetic levitation had to be overcome through a use of more advanced control strategies. These shortcomings include the nonlinear nature of attractive force as a function of coil current and air gap. Also, the open-loop dynamics of the attractive force has a strong instability that has to be overcome through feedback control. Another shortcoming is that the force is one-directional unlike the bi-directional Lorentz force (Hollis, et al, 1987), which makes the design more bulky and nontrivial. Table 1 shows advantages and disadvantages of active magnetic levitation (MSL), passive levitation, and Lorentz force based electromagnetic levitation.

type of levitation	active magnetic levitation	passive magnetic levitation	electromagnetic levitation
stability	×	○	△
low power consumption	△	○	△
control of force	△	×	○
invariability of system	○	△	△
largeness of force	○	△	△
movable range	△	○	○
freedom in mechanism	○	△	×

Table 1. Comparison of three different levitation systems

Mathematical Model of Magnetic Servo Levitation

A general mathematical model of a MSL system without specifying a special mechanism shows that magnetic servo levitation is antagonistic, or a positive-force control system. Probably the best example of a positive-force control system is found in human motor system using muscles. For example, an elbow motion is a result of antagonistic muscle motion generated by two opposing muscles. In the same way, the MSL system levitates an object by two electromagnets working antagonistically against each other. An

assumption here is that the air gap is small enough such that there exists one and only one line of force defined by the two electromagnets.

A typical model of electromagnets shows that there exists a nonlinear relationship between the attractive force/moments produced and the coil current. One assumption here is that the eddy current and the magnetization hysteresis are negligibly small. According to a simple model of steel core wound with coil at the center, the force/moment produced is directly proportional to the square of the coil currents and inversely proportional to the square of the gap length. Extending the model to describe the dynamics of a rigid body object with full six DOF's and using the nonlinear relationship between the force and the coil current show that the open loop system is inherently unstable similar to a 2nd order system with no damping and a negative spring constant.

Design of MSL System

From a mechanical design point of view, there is no difference between active magnetic levitation and MSL; the difference is all in how the systems are controlled. Referring to Fig. 1, again, a typical MSL system has two electromagnets, one on either side of the object, for single axis. This is because of the attractive nature of the electromagnets. For a n -DOF controllable MSL, it is found that the minimum number of electromagnets needed to accommodate the n -DOF control is $n+1$, which makes any MSL system an inherently redundant system. This redundancy presents a difficulty in control.

Also, a necessary and sufficient condition for locating electromagnets to ensure the n -DOF control has been found. A geometrical interpretation of the can be given as follows: Consider the n -dimensional space spanned by the column vectors of the a location matrix, whose i th column vector defines a vector of the line of force produced by the i th electromagnet. The condition states that if each of the $n-1$ dimensional hyperplanes spanned by n column vectors of the location matrix contain at least one column vector of the matrix as one of its two sides, that particular electromagnet location gives n -DOF controllable system. The condition is derived using the hyperplane separating theorem that can be expressed by a simple mathematics, and so it can be implemented in a systematic way by a computer for design synthesis. This is very important in any n -DOF MSL design in that a naive location of electromagnets often results in an uncontrollable system.

Hierarchical Control with Optimal Force Distribution for Minimum Power Consumption

As mentioned previously, the control of MSL is a difficult task because of the nonlinearity, instability, and the redundancy of actuators. Conventional control with approximate linearization results in slower response speed, large waste of power, and smaller movable range. To alleviate these problems, a hierarchical control structure has been investigated and experimentally tested for superior performances.

The proposed structure is bi-leveled: the high-level control determines desired force to perform precise force/position control based on the dynamics, while the low-level control solves the minimization problem of power consumption and performs the linearization of electromagnets with nonlinear compensation. Separating the tasks into two different levels has some merits. First, the low-level control allows the high-level control to be designed based on a simple dynamics without considering the nonlinearity or redundancy. This frees up the high-level control to employ various kinds of advanced control to minimize the power consumption. The low-level control, on the other hand, can utilize the parallel format of the hierarchical control structure to increase the sampling time that is critical for the stability of MSL.

Distribution of forces generated from redundant electromagnets for a minimum power consumption is an important issue in MSL control. When no coil current saturation is assumed, the problem reduces to a variation of linear programming in which a force vector that minimizes the power is selected from the set of all force vectors that satisfies the desired force output constraint given the location of the electromagnets. In order to reduce

the computation time, the search of all possible solutions can be done off-line. Those feasible solutions that satisfy the constraint for the particular location arrangement can be saved, and the solution that results in the minimum power consumption can be chosen in real-time. The real-time search is possible assuming the number of electromagnets are not too greater than the degree-of-freedom. When the coil current saturation is taken into account, which is the case for all MSL systems, a feasible solution may not exist. However, an algorithm using a simple extension of linear programming ensures that whenever a feasible solution exists, the solution satisfies a minimum power requirement for that particular location of electromagnets.

Adaptive Control without Velocity Measurement

In general, MSL provides a near-ideal system for precision mechatronic applications because of the absence of mechanical uncertainties. However, some uncertainties arise from inaccurate magnetic parameters and from the difficulty of measuring the velocity of a levitated object. An adaptive control is necessary to alleviate some of the problems due to these uncertainties.

However, most of conventional adaptive schemes can not be applied directly to MSL the full-state feedback requirement, which necessitates velocity measurement. The significance of the adaptive scheme developed at the Higuchi's laboratory is that an adaptive observer is utilized that estimates the velocity from the gap sensor measurement to not only stabilize but also to achieve desired tracking in the presence of the uncertainties.

A Lyapunov based adaptive scheme is constructed using both the tracking error and the state estimation error. Conventional adaptive observers use just the state estimation error. The strategy adopted for MSL is one that fuses the concept of adaptive control with that of auxiliary filter that functions as an adaptive observer. Stability and the error convergence both for the tracking as well as state estimation are proved using the Lyapunov's direct method, and the system performs well without the velocity measurement. Possibility of identifying some magnetic parameters using the same approach is being investigated.

DSP (Digital Signal Processor) Based Digital Controller

One major issue in realizing a controller for MSL is that of the sampling speed. Strong instability present in the open loop dynamics requires a fast and efficient controller to close the loop for stability. Although an analog regulation controller used in a conventional magnetic bearing system is faster than a digital one, nonlinearities and other features of MSL require the system to be digitally controlled. Also, implementation of the control schemes mentioned previously needs complicated computation which desires a digital controller.

Single-DOF digital controller using DSP is first developed, followed by a Multi-axis digital controller based on centralized, hierarchical control structure using DSP's. The DSP's used are μ PD77230's made by NEC with hardware clock speed of 13.3MHz which can perform the floating-point multiplication and addition in 150 ns. The host CPU is a 80286 with 80287 math coprocessor by Intel.

For general n -DOF multi-axis controller, $k+2$ DSP's, n A/D converters with low-pass filters, k D/A converters with current amplifiers, and a host computer are used, where k represents the number of electromagnets. According to the structure adopted, the DSP's mainly take charge of the stabilizing the closed-loop axes control, while the PC takes charge of overall command generation and distribution. Both the DSP's and the host can be interrupt driven from each other.

Applications

Numerous applications of MSL have been investigated. The first, and arguably the most publicized, is what is coined as MEISTER (Magnetically End-effector-levitating

Instrument for a Skilled Task-undertaking Expert Robot), developed in cooperation with the University of California at Santa Barbara for precision and flexible assembly (See Figure 2). The celebrated features of the MEISTER are (1) programmable compliance: the compliance and the viscous damping of supporting an end effector can be magnetically changeable by software; (2) precision multi-DOF actuation: the position and attitude of an end effector can be accurately controlled by changing magnetic force; and (3) multi-axis force sensing: external forces and moments acting on an end effector can be computed without any force measurement. All these functionalities enable the MEISTER to be used as an advanced/active remote center compliance device to correct for a micron level misalignment in the insertion task. The resolution of the force/moment measurement achieved by the MEISTER is 0.04 N/0.001 Nm.

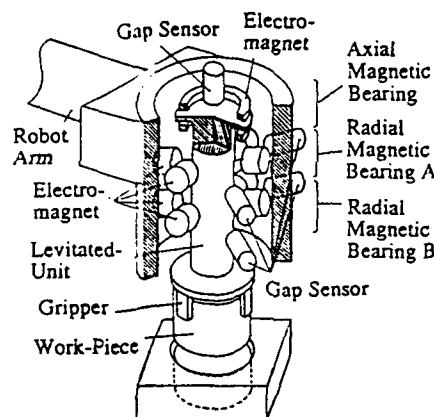


Figure 2. Schematic of a prototype of the MEISTER

Another application of MSL has been found in the area of precision machining. A single-axis cutting tool holder mechanism using MSL has been designed and built. The holder serves as an auxiliary unit that provides a high bandwidth, small range tool motion correction for a non-circular profile machining. Problems of heat generation and eddy current effect aside, the system performed reasonably well achieving 60 Hz bandwidth within 2 mm motion range. The accuracy of the system was about 1 micron, which was limited by the gap sensor used.

For this system, since the stiffness of the system was provided solely by the servo loop, the high gain solution was required. However, this solution in general requires a large power consumption. The stiffness of the system had to be improved through a mechanical means in which the tool was held by a set of mechanical springs. This resulted in an improved bandwidth as well as power consumption reduction.

Other application was found in micro drilling where very thin drill bits are used to drill holes whose diameters range in the tens of microns. The idea here was to levitate the work-table via MSL in a force measuring mode in such a way to comply to any bending of the drill bits. Without some sort of compliance built into the system, the drill bits are easily broken or the accuracies of the hole size as well as the shape are affected.

Current research topics in the area of MSL involves improving the accuracy by identifying some magnetic parameter uncertainties and sensorless MSL by monitoring the internal parameters such as current. Probably the most significant factor in keeping the MSL system from a wide use is the economic one. Research such as sensorless MSL is going on to reduce the cost of realizing the system, thereby making the system more

practical. The following sections on use of permanent magnets and LC tuned circuits for active magnetic suspension represent some efforts along this direction.

B. Magnetic Suspension Using Permanent Magnets

Magnetic suspension using permanent magnets is an on-going effort that deserves a brief look. This work is being studied by Mr. K. Oka, who is the laboratory assistant in the Higuchi Lab working toward his Ph.D. degree. Although this work is at its initial stage, and only some preliminary results are available so far, the approach offers some fresh perspective on magnetic levitation. The main motivation behind the use of permanent magnets over electromagnets is that of heat generation of the latter which causes excessive power waste. In the new approach, the forces of permanent magnets are used for levitation and are controlled by adjusting the reluctance of the magnetic circuit. The principle of this approach and the typical control methods of changing the reluctance are investigated, and the experimental prototype system for a single-axis vertical levitation is demonstrated.

In the initial work, two types of reluctance control methods are investigated. In the first method, reluctance is controlled by introducing magnetic saturation of a ferromagnetic body. This is achieved by making a gap in the ferromagnetic material that surrounds the permanent magnet, and controlling the gap volume by inserting a movable ferromagnetic element into the gap. The relative displacement of the element in the gap produces the same effect as the change in resistance in an equivalent circuit of the system. Depending on the shape of the ferromagnetic body that surrounds the permanent magnet, different reluctance of the overall system results as a function of the variable resistance.

The second method for controlling the reluctance is achieved by controlling the air gap between the permanent magnet and the levitating object. (In the first method, the air gap was assumed to be fixed.) This approach was used to develop a first prototype system whose schematic is shown in Figure 3. Adjusting the air gap is done by a voice coil motor which moves the permanent magnet above the iron ball, a levitating object, along the vertical direction. If the iron ball moves toward the magnet from an equilibrium position, the position of the iron ball is detected by the eddy current gap sensor placed under the ball, and the feedback signal is fed back into the voice coil which bring the magnet upward to establish a new equilibrium position, and vice versa for the downward movement.

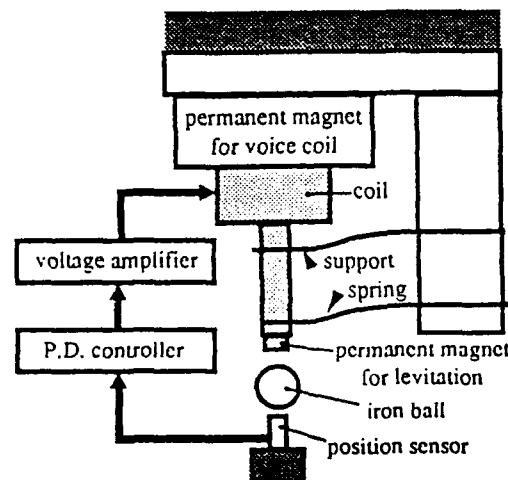


Figure 3. Schematic of PM based Levitation System

In the actual implementation, the permanent magnet structure is secured by a set of cantilever springs for better stability and faster response speed. A linear compensation scheme using a PD control was used to control the reluctance, and the resolution of the response was about half a micron. Actual experimental plots of step responses agree quite well with the simulated responses; yet, the performance issues such as oscillation and the speed of response need to be further addressed.

C. Magnetic Suspension Using Tuned LC Circuit

Motivation behind developing a magnetic suspension using tuned LC circuits is an economic factor in that it offers a simple design that does not require sensing. The technology is based on the variation of inductance of an electromagnet, which is a function of the gap between the electromagnet and the suspended object, to modify the force-displacement characteristic of the levitation system. Figure 4 shows a single DOF magnetic levitation system using a tuned LC circuit. The electromagnet represents the inductive part of the LC circuit.

The LC circuit is designed in such a way that when the levitating object moves away from the electromagnet, inductance decreases. This decrease in inductance will cause the LC circuit to resonate, which results in increasing the coil current and, therefore, the attractive force. The increase in force then restores the object to its original equilibrium position. When the object approaches the electromagnet, the LC circuit leaves away from the resonant state. The resulting decrease in coil current reduces the force, and the object is pulled away from the electromagnet by the gravity until the original equilibrium is restored, again.

A main issue to be concerned with is that of obtaining a stable equilibrium point for the object. Unfortunately, the system tends to vibrate divergently, and therefore becomes unstable without the presence of some sort of damper (therefore, the damper in Figure 4). Generally, an oil damper is used by submerging the object in oil. This has limited the application of LC circuit based suspension to some specialized fields. Another limitation has been the complexity involved in the theoretic analysis of the tuned LC circuit behavior.

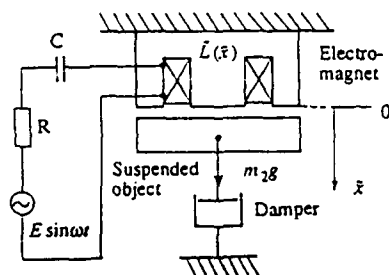


Figure 4. Conventional Tuned LC Design

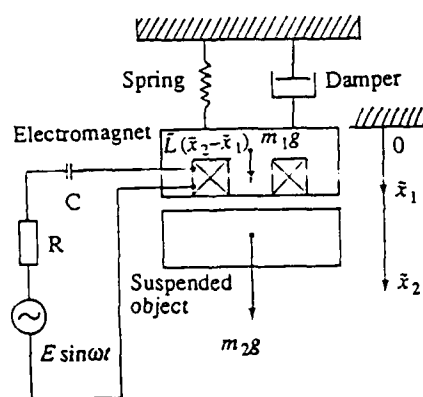


Figure 5. New Tuned LC Design

Work at Higuchi Lab, done by Dr. Ju Jin, a former Ph. D. student under Prof. Higuchi, attempted to alleviate some of the problems so as to promote further research and applications for this particular type of levitation technology. The first thing was to obtain a simple yet effective model for the dynamics associated with the levitating mechanism. They achieved in developing a linear transfer function model of the dynamics which predicts the inherent instability of the system. In order to stabilize, a new indirect damping method was developed which proved to be working. Figure 5 shows the levitation system using the new scheme. Differences in the new design are that the stator, the inductive element, is movable and that the damping is applied to the moving inductance instead of the levitating object. The damping effect is transmitted to the object through the attractive force, and as a result a stable levitation is achieved.

Because of the absence of sensors, the accuracy of levitation is a function of how accurately the LC circuit is tuned and the approximation involved in obtaining the transfer function model. Experimental results show that the accuracy is poor compared to other sensed levitation systems and the performance has much room for improvement. Nonetheless, the new scheme offers advantages of possible servo levitation just by virtue of the fact that the electromagnet is movable and application of more advanced control to improve the response performance of the tuned LC circuit based levitation.

III. ULTRASONIC MOTOR

Dr. Kurosawa joined the Faculty of Eng. at the University of Tokyo in Jan. of 1993, and has been an Associate Professor working with Prof. Higuchi since then. He is an expert on ultrasonic motors, and has produced numerous papers on the theory, design, and experimental aspects of various types of ultrasonic motors.

Ultrasonic motors, powered by ultrasonic vibrating energy, instead of electromagnetic energy, induced typically by, but not limited to, PZT elements. The general principle behind these motors is the use of traveling waves propagating along an elastic object. When a moving object is pressed on to the elastic object, the frictional force associated with the travel wave surface causes the object to move. The direction and the speed of motion can be changed by switching the propagating direction of and the frequency of the wave. The active research on these motors is fueled by current interest in micromachines and actuators. Advantages of these ultrasonic motors over conventional electromagnetic motors are their relatively small size and larger torque output.

Over the years, Dr. Kurosawa developed many different types of ultrasonic motors. There are linear types as well as rotary types, all of which utilize the PZT stacks polarized in various directions to induce necessary traveling waves. One of the earlier versions developed utilized bending vibrations of a short cylinder with free-free ends. In this motor, two PZT ceramic disks are sandwiched between two stainless steel cylindrical blocks, with their poling directions facing one another. The whole unit serves as an elastic stator whose bending vibration is induced by four (2 pair) electrodes laid in between the PZT disks. Traveling wave is induced by inputting a sinusoidal wave into a pair of electrodes and the same signal but 90 degree out of phase into the second pair. In this way, two standing waves 90 degrees in phase produces a traveling wave along the circumference of the cylindrical blocks.

When the rotor is finally pressed on to the either end of the block, the rotating motion is generated, whose rpm depends on the input frequency (45kHz in this case corresponding to the bending mode of the cylindrical block) and the frictional material used for the interface between the stator and the rotor. Higher power efficiency and the speed were achieved by using a special frictional material of a thin layer of cyanoacrylate instant adhesive. However, the maximum efficiency that could be achieved with this kind of vibrational motors was about 9.0 %, which leaves a room for significant improvement. A main reason for such a low efficiency is attributed the design of the stator in that the vibration mode has an undesirable radial component. Also, the frictional material used at the interface makes a significant difference as mentioned.

Naturally, the design goal of ensuing systems was to increase the power efficiency and therefore the torque output of such motors. This effort resulted in hybrid transducer type ultrasonic motors which have 33% power efficiency. Figure 6 shows the basic schematic and the principle of operation of such a system. The main difference here was a use of a different type of stator that consists of two kinds of PZT devices. One controls the frictional force and the other generates the output force. Multi-layered PZT stacks are mounted between the stator and the rotor, and by controlling the length, the frictional force is modulated, while Multi-layered torsional (bolted Langevin type, or electrostrictive type) transducers generates the torque. In the latter case, the torsion is generated by producing arbitrary Lissajous figures at the interface surface, which then travels circumferentially according to the same procedure as in the bending mode case. The maximum theoretical efficiency is obtained when the velocity of the vibrator is constant and equal to that of the rotor at the time of contact. So, the velocity profile for the torsional vibrator looks like a sinusoidal signal with flat top at about three quarters of the amplitude. Selection of the friction material is also important to maximize the efficiency in this system.

Another type of ultrasonic motor investigated is a linear motor traveling on a thin

aluminium bar. A prototype of such system claims to achieve 1m/sec traveling speed with superior transient response characteristics to a magnetic linear motor. The details of the principle and the construction of a prototype for this system is resorted to a paper written by Dr. Kurosawa in the Ultrasonics Journal (1989 Vol 27, Jan).

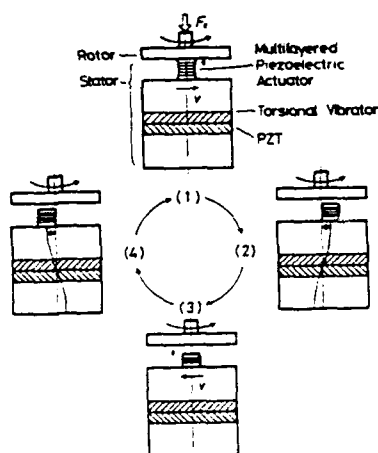


Figure 6. Principle of Hybrid Transducer Type Ultrasonic Motor

IV. ULTIMATE MECHATRONICS AT KAST

The Kanagawa Academy of Science and Technology (KAST) is located in the Kanagawa Science Park of the Kanagawa Prefecture about 30 miles southwest of Tokyo. The foundation was conceived back in October of 1987 under the tentative name of Kanagawa Science and Technology Promotion Organization, and it was officially authorized by the prefectural government in July of 1989.

The basic tenet of the KAST is to "engender advanced technological innovation in the 21st century" so as to conquer many of the problems that are faced by mankind and the earth such as environmental ones and to use science and technology developments to benefit future mankind and the earth.

The foundation is composed of three main activities, which are research, education, and exchange activities. Of these, research activities comprise a large portion. Within research activities, there are currently 10 laboratories, individually headed by a project head, carrying out research in various fields ranging from biotechnology, materials, and mechatronics. Each project has either 3-year or 5-year term, depending on the size and the field. More recently, all research projects have adopted 5-year terms. The budget for each of the projects varies from project to project.

Overview of the Ultimate Mechatronics Project (UMP, Higuchi Project)

The UMP is located on the fourth floor of the East Wing of KAST. The Ultimate Mechatronics project has an overall budget of 9.6 million dollars for 5 years, which works out to be about 1.9 million dollars per year with no overhead. The lab space for the UMP is about 4000 sq ft (375 sq meter). Under Dr. Higuchi's headship, there are eight full-time research associates, six full-time students doing their theses work, and an administrative staff person. In addition, there are twelve research associates from the member companies resident at the lab.

The UMP was initiated in the April of 1992 and will be completed in March 1997. The scope of the project divides into largely two broad categories: Ultimate Environment Mechatronics (UEM) and Ultimate Function Mechatronics (UFM). Under UEM, there are two main thrusts; one in Ultra-High Vacuum Mechatronics and the other in Cryogenic Mechatronics. Of these, the former focuses on applications such as semi-conductor technology which will continue to take advantage of the ultra-high vacuum for minimum impurities. In an ultra-high vacuum environment, there are restrictive conditions preventing the use of common mechanical elements designed for standard environments. It is expected that robots incorporating magnetic levitation technology will enable semiconductor production without the need for a clean room. In the latter case, the development of systems exhibiting minimal thermal noise is the focus. For this purpose, actuators equipped with new mechanisms that integrate piezo-electric devices and superconductive materials will be developed.

Under UFM, there are three main thrusts. The first one is in the area of ultra-precision mechatronics, where surface fabrication with angstrom accuracy, ultra-precision positioning accuracy, and STM based feedback control scheme development are of main focus. The second area, called Micro-Mechatronics, has to do with ultimate miniaturization of automated machinery including robots. A central focus here is the development of micro-actuators driven by electro-static power. Theory and the implementation issues pertaining to these actuators are being developed along with optimum production methods. Lastly, Bio-Mechatronics area has its focus on manipulation and observation of three-dimensional in-vivo micro-organisms such as DNA. A device being developed is a genetic information reading system that may utilize a STM or an AFM to resolve the structures of DNA molecules down to atomic accuracy.

A. Electrostatic Film Actuator

The work on electrostatic actuator started back in 1987 by Mr. Saku Egawa, who then was a Master's student under Dr. Higuchi. The work started with a desire to develop an artificial muscle with high power-to-weight ratio such as those equivalent to human muscle (100 - 500 W/Kg). The development of such actuators can revolutionize the way the robots are used. The biggest bottleneck of conventional robot manipulators are their bulky electromagnetic motors that produce very small payload-to-weight ratio. By their latest version of the electrostatic drive system developed by Mr. Toshiki Niino, the power-to-weight ratio of 230 W/Kg has been already achieved, which is equivalent to average adult human muscle.

The original version was called the image charge stepping actuator, in which a flat stator with striped electrodes covered with isolative material induces charges on a slider that consists of isolator and a high resistor layer (a little bit of carbon is added for a slight conductivity of the slider). The slider is driven through the charge induction stage and the actuation stage. The charge on the slider is induced first by supplying a combination of positive and negative voltages into three-phase electrodes on the stator. After certain time, the charges move through the resistor and produces "mirror image" charges on the slider. After charges are sufficiently induced, the signs of voltages applied to the electrodes change in such a way to produce a repulsive force vector that has components both in lifting as well as shifting. The lifting force eliminates the friction force between the slider and the stator and the shifting force moves the slider to a given direction. The procedure then can be repeated and the speed can be adjusted by varying the frequency of switching the voltage. The switching voltages used were 1 kV either direction. One of the prime importance in the design of these actuators are the resistivity of the slider. Too much of it will produce too long a time lag to produce a mirror image charges, and too little of it will not be sufficient to allow enough time lag for the image charges to bleed off for motion generation.

The original design has been modified over period to produce higher power-to-weight ratio needed to equal that of human muscle. Among the variants are a two-phase motor for simplicity in design and fabrication and the Ion-Charged motor which utilizes ion shower device to induce charges on the slider by utilizing a thin film of ionized air between the slider and the stator. In the latter case, potentials applied on the electrodes attract ions of opposite polarity and leads on the slider the same "mirror image" charges on the slider as in the original version. Another version was developed using a transparent stator layer made of indium tin oxide (ITO) material. Although these variants operated under different principles, there was not much improvement in the resulting power-to-weight ratio from the original version.

A breakthrough came about when Mr. Toshiki Niino, then a Master's student working under Dr. Higuchi, started using charged electrodes for the slider as well as for the stator. The first version of the what has been named a variable capacitance motor with active slider (VCMA) had a four-phase slider with a three-phase stator. Conceptually, the idea of switching the voltage to produce both the lifting and the shifting forces was the same; however, the system had an added feature of closed-loop control with current sensors that can monitor the position of the slider with respect to the stator. The closed-loop control provided maximum available forces for any given slider position, and therefore, helped achieve higher power-to-weight ratio to about 17 W/kg. Still, the major bottleneck to achieving even higher power-to-weight ratio was the bang-bang type nonlinear switching of voltages that results in much power loss in discharging and recharging of electrodes. This idea led to use of sinusoidal switching rather than bang-bang switching. The sinusoidal switching has two advantages. Not only does it allow for

slower energy loss because of smoother switching, it also permits the use of much more efficient devices for amplification that are commercially available.

Finally, the design that incorporates sinusoidal switching with three-phase stator and slider has been developed. Figure 7 shows this improved design schematic along with traveling waves for the stator and slider. Because of smoother switching, the maximum switching voltage of 2 kV was used instead of 1 kV. This brought about a significant improvement of power-to-weight ratio. Also, in the final design, both the slider and the stator use the same voltage source, just the opposite polarity to produce a traveling wave effect at the interface. Multi-layered concept can be easily implemented on all of these designs because of the flat nature of the design. So, to produce a needed power, one only has to stack these sheets of actuators in multiple layers. In fabrication, the multi-layered actuator is immersed into dielectric fluid, "Fluorinert (3M)", to reinforce the dielectric strength of the interface.

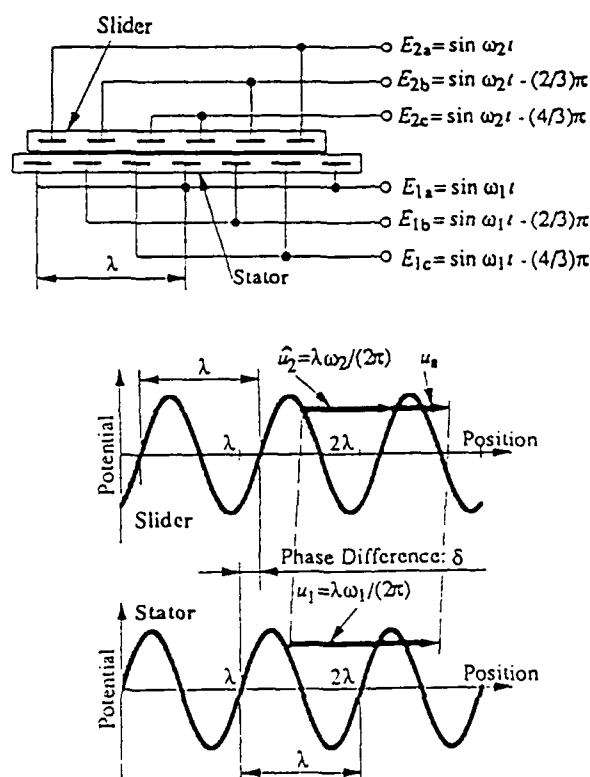


Figure 7. Improved Design Schematic with Dual Switching and Traveling Wave Forms

The control aspect of the project still needs some improvement; however, it should be noted that the main focus of the project has been to improve the power-to-weight ratio. Currently, work is going on to improve the control response behavior as well as the repeatability of the drive system.

Discussion with Mr. Egawa, a Ph.D. student of Prof. Higuchi who came up with the original idea of using electrostatic force for the current film actuators, focused on hardware, control, and application aspects of the film drive system. The first topic discussed was a possible application of the film drive system to nanometer position control. The system's position resolution is limited by the gap length between any two electrodes. Mr. Niino's actuator can achieve the positioning resolution of $1/12$ of the 3 phase electrodes spacing, or roughly $1/2$ of the gap length. Currently, the gap length of 50

micron has been achieved. The limit of the gap length is not due to the IC etching technology. It is limited by the surface roughness at the interface between the stator and the slider. For example, if the surface roughness in the order of 10 micron is present, the gap length of 1 micron would not produce an appropriate electrostatic force field for the film actuator principle to work. The exact force field is being calculated through FEM to see what the exact limit is. Current effort is concentrated on miniaturizing the actuator, so to make it more practical (this produces an effect of reducing the voltage input level from 2kV to something more practical) for many industrial application including robots.

Control bandwidth issue was raised as well. In order to apply such actuators to industrial manipulators, an accurate model of the actuator-amplifier system has to be obtained and their dynamics well characterized to predict its behavior and performance. What limits the control bandwidth of the actuator system is not quite well known, because the dynamics is not characterized at all. Frequency response of the actuator system might be desired to see what kind of poles and zeros are present and what they actually represent physically. A comment was made as to the fact that, since the system is a synchronous type motor, it is not trivial to produce a frequency response plot of the actuator system. Whatever the case, the maximum achievable speed of the system is about 1 meter/sec which is a significant achievement. The actuator, in case of non-electrode slider, can be modelled simply as a gain because of its static nature with a negligible time lag.

A demonstration of the system exhibited a limit cycle like behavior when a critical mass of 2 kg force was added. The system shook vibrantly as the weight was being lifted. A long discussion was held to find the cause of such behavior. From a stability point of view, a likely cause could have been a saturation related nonlinear limit cycle behavior. However, the performance of the system is not optimized at all at this point, so the vibration might be due to a lack of damping control in the system. A mechanical damper, or a more sophisticated control scheme, can be applied to increase the damping as well as the gain margin of the system. It was mentioned that the force is directly related to the phase difference between the two opposing sinusoidal waves of the stator and the slider, and the phase difference in turn is a function of the time and the distance traveled. This time varying aspect of the output force makes the system harder to deal with in characterizing as well as analyzing its behavior. Anyway, dynamics and the stability limit of the weight lifting should be more carefully analyzed to obtain correct understanding of the vibratory behavior observed. It was generally agreed that the system needs to be better characterized and the application well defined before a more advanced control scheme can be devised.

It is just a matter of time before we see a robot manipulator driven by a set of these powerful actuators. What needs to be pursued is the controller suitable for optimizing the behavior and stability of these actuators. In the Higuchi's Lab, there is a miniature version of an industrial robot arm driven by two sets of the electrostatic actuators that performs a simple teach-and-play-back routine of lifting and placing an object.

B. Impact Drive Machine

Work on the Impact Drive Machine (IDM) is being pursued Dr. Yamagata, who did his Ph.D. work under Prof. Higuchi and is currently a full-time research associate at KAST working on Precision Diamond Turning aspect of UMP. The IDM is a precise position mechanism that utilizes a rapid deformation of piezo-electric elements, that can achieve a nanometer position resolution with virtually unlimited range. The idea is similar to the inch-worm concept, except in the case of IDM no extra clamping mechanism is needed. Clamping presents a significant complication to the control of inch-worm devices because of signal synchronization, unnecessary vibration generation, and clamping accuracy. IDM

has all the features of an inch-worm device without all the problems associated with clamping.

The original idea about IDM was conceived by Dr. Higuchi and was pursued by Dr. Yamagata as his Master's thesis topic back in 1988. The best way to understand the principle behind IDM is first to imagine a stack of piezo-electric elements attached to a wall on one side and a weight on the other side. If the stack is subjected to a sudden change of voltage command input, the stack will either contract or expand rapidly, which in turn accelerates the weight. This acceleration of the mass of the weight will generate a reaction force on the wall. Now, imagine taking the wall out and replacing it with an object held only by friction. If the reaction force generated is greater than the friction force holding the object, then motion will be generated on the object in the direction opposite to the motion of the weight. It should be noted here that the force generated is directly proportional to the amount of acceleration experienced by the weight, which in turn is related to the rate of change of the voltage command. So, if the voltage command is restored to the original level slowly relative to the first case, the stack is back to the original length, only this time the reaction force was smaller than the frictional force, and the object remains stationary. So, by repeating this process of sudden drop or increase (depending on which direction) of voltage command followed by relatively slow restoration, a series of steps can be generated for the object along a given direction. Figure 8 summarizes this principle explained above. One can easily recognize that there is no limit to the range of motion, which in practice will be limited only by the sensing mechanism.

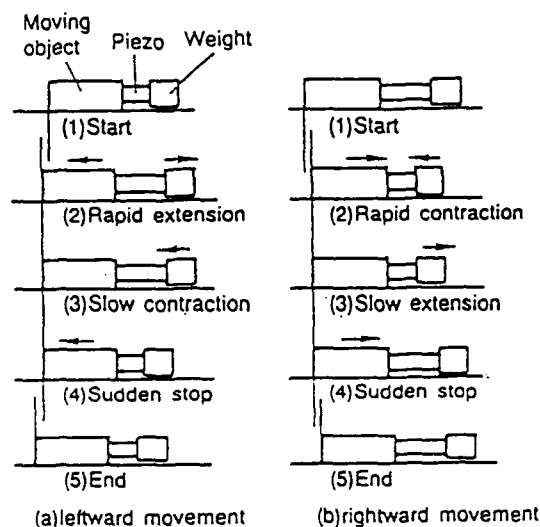


Figure 8. Principle of Motion for Impact Drive Machine

In his dissertation, Dr. Yamagata devised a simple yet effective way of modelling the characteristics the piezo-electric stack by using an electrical network analogy. The model he developed not only produced a very accurate prediction of the system behavior but also provided an efficient means to examine IDM's characteristics under parameter variation. Some of important parameters essential to its design and performance are the weight-to-moving object mass ratio, frictional force holding the object, rates of stack deformation and restoration which have to do with voltage command generation, the pulse

rate (how many deformations per second), and the command voltage amplitude. Based on experiments, an optimum operating condition was obtained at around 6.2 kHz pulse rate at 0.4N frictional force, which resulted in 0.9mm/sec maximum velocity with the voltage amplitude of 50 V.

The IDM is patented in Japan, the U.S.A., and Europe, and a commercial slideway using the IDM concept is being produced by at least two companies in Japan. Several applications of the IDM were studied in cooperation with industrial sponsors. They are IDM-driven micro-robotics, ultra-high vacuum precise positioning, a roundness error measurement, and biological cell manipulation. Different applications utilize a variety of features that the IDM system can offer. In case of micro-robotics, attractive features include simplicity and compactness of design along with high resolution it can afford. Another important area is ultra-high vacuum manufacturing. For fabrication of VLSI circuits and manipulation of surface analysis instruments such as STM or AFM in vacuum, a high-precision positioning device which is capable of making a few nanometer step to a few micrometer step with a minimum outgassing is required. A STM using IDM is constructed recently that operated successfully in a high vacuum chamber of the order of 10-12 Torr. Yet another application of IDM was in devising a one-dimensional micro-manipulator for inserting a capillary into the elastic membrane of an animal egg embryo. The manipulator makes a step-like motion which makes it ideal to puncture into an elastic membrane. A conventional drive system will deform the entire membrane without a puncture because the motion is much smoother than the IDM.

From controls point of view, one of difficulties arises from irregular frictional force due to surface irregularity, in-trapping of foreign materials in the interface, and etc. An adaptive scheme has been devised to deal with this problem, and a general improvement has been shown. More detailed analysis as well as development of more advanced controllers for the IDM system are desired. A current work on IDM has to do with miniaturization of these systems for various applications including genetic information manipulation. Issues involved in the miniaturization are those of manufacturing as well as scale factors that would have a definite bearing on characteristics of the IDM systems.

V. AFTERTHOUGHTS and ACKNOWLEDGEMENT

This project was very valuable on many respects. First, the project provided for the PI a wonderful exposure to a world of mechatronics and insights into where it is heading in a way that could have never been possible otherwise. Indeed, the quality of the research work, as well as the staff and the facility, at the University of Tokyo and the KAST was superb. Prof. Higuchi is definitely one of the best and the most active in the field of precision mechatronics, if one may use the term. Also, the related visits to different companies and laboratories served in understanding not only the depth but the breadth of mechatronics effort in Japan. With the current boom in MEMS research, precision mechatronics work is receiving a greater attention from academia as well as in industry. The world will need better performance actuators to run higher efficiency, faster, more precise, and increasingly smaller-sized machines.

Secondly, the project served to identify some of current problems and further research topics in the area of precision actuators design and control. Discussions with Prof. Higuchi, other staff members and students were essential not only in understanding some of the intricacies of the concepts and techniques developed but also in identifying weak links that needs further research. Also, the project served to create a valuable pool of contacts in Japan who are working in precision mechatronics area, with several of whom I made friendship that will go beyond just a mere acquaintance.

Lastly, but not least, the stay in Tokyo was personally quite gratifying. Aside from the hand-and-head sign language that I often resorted to, subway rides full of people and high cost of living, it was indeed an experience that will last a life time. I appreciated the kindness of the people, cleanliness of public places, the food, all those late night walks without any fear of getting mugged, and many more.

The foreign science analysis program of the ONR was an excellent venue for me to acquire information that I wanted, to broaden my research horizon, to meet new and important people, and to enjoy every minute doing all these all at once. In retrospect, however, I wished that the trip was a little longer than 5 weeks; at least three month long. Five weeks was too short in terms of what I could contribute to the existing research programs of the host professor. It became apparent over the course of the visit that it is important not only just to acquire as much as one can from the host but also to make a strong impression that the host benefitted from the visit as well. The only way to do this is to allow a sufficient exchange of information and to be involved in one of existing research projects.

Finally, my deep appreciation goes to Dr. Toshiro Higuchi and Dr. Andre M. van Tilborg for making the experience possible for me. Also, my thanks goes to Dr. David Kahaner for the visits he arranged and for all the information that he made available, to Dr. Ren Luo for a wonderful dinner and the friendship while in Tokyo, and to all the staff members at the KAST and the students at the University of Tokyo for answering all those questions with patience and utmost kindness. Thanks to Christine, Michelle, and Pauline for putting up with my absence.

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APPENDIX

Daily Minutes of the Visit

Week 1 (5/24 - 5/28/93)

Mon

- Meeting initiated at Prof. Higuchi's office
- Met with Dr. Kurosawa, who is the Associate Prof. of the Higuchi Lab and who also is an expert in ultrasonic motors; he is from Tokyo Institute of Technology
- A simple lab tour by Dr. Higuchi showing three different experimental setups, all having to do with magnetic servo levitation (MSL)
 - 1) 5 DOF MSIH hand for precision assembly
 - 2) MSL system for micro-drilling
 - 3) 3 DOF planar assembly system
- * note: all have been designed by Dr. Masahiro Tsuda

Tue

- Basic setting-in procedures
- Set up computer systems for word processing
- Set up E-mail address for communication with students

Wed

- First visit to KAST, Kanagawa Academy of Science and Technology, located at Kanagawa Prefecture
- Meeting with Dr. Higuchi on the overview of the KAST and the Ultimate Mechatronics Project
- Simple Lab tour by Dr. Higuchi and Lunch
- Meeting with several key researchers including Dr. Yamagata who will be in charge of precision diamond turning area of the UMP

Thur

- Reading of Dr. Tsuda's Ph.D. thesis which provides a comprehensive and thorough information on MSL
- Discussion with Dr. Kurosawa on ultrasonic motors and a simple demonstration; several of key papers authored by him have been obtained

Fri

- Discussion with students about various Magnetic bearing based projects
- Getting in more depth into Dr. Tsuda's Ph.D. thesis, especially the applications of MSL in micro-drilling and assembly
- Chat with Dr. Higuchi on various topics including the history behind MSL. He recognized the inability to control the gyroscopic dynamics of magnetic bearing systems, and the need to actively control it for better performance led to MSL.
- Obtained a free copy of the proceeding of the 2nd Magnetic Bearings conference held in Japan organized by Dr. Higuchi and the Institute of Industrial Science

Week 2 (5/31/93 - 6/4/93)

Mon

- Discussion with Mr. Jeon who is a first-year Ph. D. student under Dr. Higuchi, who is currently working on developing advanced control scheme for both micro-drilling and precision assembly using Magnetic Servo Levitation
- Read a paper written by Dr. Hollis of IBM on implementation of magnetically levitating master (MLM) manipulator for driving a STM.
- Wrote a simple white paper (preproposal) for extending MLM idea for driving a micro-robot for eye surgery

Tue

- Second visit to KAST; met with Mr. Niino, 2nd-year Ph.D. student under Dr. Higuchi, working on development of high efficiency high power electro-static muscle-like actuator. A separate report has been written for this meeting. He went over four MEMS proceeding papers covering the entire history of electro-static drive systems in Higuchi's lab, and showed a video of working prototypes. I was advised not to take any pictures unless the pictures are already published.

Wed

- Studied MSL application in precision assembly, Part II of Dr. Tsuda's Ph.D. thesis, general control scheme of changing the stiffness of the MSL device understood
- Mr. Jeon showed the micro-drilling set-up and precision assembly set-up, a planar case, in operation. Much were not functional, or fully operational. However, 10 micron clearance insertion is demonstrated.
- Discussion with Mr. Jeon about a possible thesis topic on Nano manipulation using MSL. Some problems are bandwidth limit, eddy current dynamics, noise filtering, and sensing issues and more.
- Took some pictures of the MSL devices in the lab and ultrasonic motors upon Dr. Kurosawa's consensus

Thur

- Read three papers on H-infinity control application to magnetic bearing that were published on 2nd and 3rd Int'l Conf. Proc. on Magnetic Bearing. The papers were authored by Herzog and Bleuler at Institute for Robotics, ETH Zurich, Switzerland, and M. Fujita, et al, at Kanazawa University, Dept. of Electrical and Computer Eng.
- Discussed with Mr. Song, a Ph.D. student under Prof. Higuchi, working on laser CD disk centroid alignment control using PZT driven control mechanism. Fuzzy control of misalignment regulation suggested for a possible topic of research

Fri

- Visited the KAST facility for the third time. Discussed with Dr. Yamagata on Impulse Drive Mechanism. A separate report was written for this IDM history and principle. Two sets of video are shown about several applications of IDM including ultra-high vacuum, biological cell manipulation, and micro-robotics

Week 3 (6/7 - 6/11)

Mon

- Papers on ultrasonic motors are read and a brief summary has been written. A brief discussion with Dr. Kurosawa about the theory aspect of these motors was held. Raising the efficiency of the power input to work output has been the key issue in development of various kinds of motors. The work started with examining the vibrational modes of a circular ring, and moved on to bending mode of a cylindrical solids. Recently, a hybrid type utilizing the bending and the torsional modes of cylindrical solid is investigated.

Tue

- A meeting with Mr. Egawa, who first conceived the idea of developing a linear motor using electro-static force, was held. He is currently a Ph.D. student of Prof. Higuchi, and is writing a thesis on film actuators. A useful information about the hardware as well as control limitations of such actuators are obtained. A separate report has been written on this meeting. Mr. Egawa is currently working with Hitachi to identify a suitable application of the film actuator. He is working on miniaturizing the system to make the system more practical in terms of power requirement. It currently requires 2kV AC power supply which is a little out of scope for most electronic equipments.

Wed

- Holiday because of the Royal Wedding was held in Japan. Took a break and wrote to people.

Thur

- Took care of administrative things in the morning, corresponded with students at NCSU
- Visited the Institute of Industrial Science (IIS) at Roppongi for their annual open house in the afternoon.

- met with Dr. Kawakatsu and discussed about his projects on two-tip STM, Laser photodiode based linear magnetic drive, and world's smallest magnetic drive
- met with Dr. H. Fujita - micromechanical systems, electrostatic microactuators, thermobimorph actuators, parallel cooperative MEMS, Ken Gabriel's counterpart in Japan
- met with Dr. T. Masuzawa - micromachining research, EDM based drilling, microassembly, micronozzle fabrication, micro 3D shape measurement

- A brochure on mechatronics effort in IIS is obtained

Fri

- Visited Hitachi City, a conference on magnetic bearing, a Japanese proceeding obtained.
- Met Dr. Okada of Ibaraki University, the chairman of the conference
- Took a tour of Hitachi Works - a producer of MLV using Nb-Ti superconducting material and large capacity gas turbines; Dr. Mizuno of Saitama University (MSL controls expert, former assistant to Dr. Higuchi) was accompanied, no picture could be taken for the tour
- Discussed with Dr. Mizuno on possibility of applying MSL to diamond turning. Pointed the importance of sensor, frequency based cap gage sensor; hybrids of PZT with air bearing, air bearing with MSL, or MSL with PZT were suggested.

Week 4 (6/14 - 6/18)

Mon

- Had a meeting with Dr. Higuchi at KAST. Discussed about Ultra-precision Mechatronics
- cylindrical version of film actuators are being developed for miniaturization. Diamond Turning is being utilized to produce the winding on a cylindrical column. Main idea is micro-machining using conventional machine tools. - Dr. Higuchi had a invited talk on this topic at 1993 MEMS. (A copy of this obtained) Toshiba's DTM is purchased for this purpose.
- Mr. Oka's work on levitation by permanent magnet and linear voice coil is demonstrated. A paper on this topic is obtained. Control is a simple closed loop control based on gap sensor feedback. Bandwidth is about 20 hz, and the system is quite stable even with vertical disturbance. The horizontal position is held by the potential field of the permanent magnet. The optimum magnetic field was obtained for horizontal stability when a PM of a

cylindrical shape with a hole in the middle is used. DSP based control with a coaxial gap sensor is being pursued at this point. Not sure about specific applications of the device.

Tue

- Visited Hardy Barracks to meet Dr. David Kahaner for the first time. A possibility of doing another 6-month to 1 year stint at U. of Tokyo was discussed, but not fully pursued.
- Visited Micromachine Center (MMC) at Yokohama area. David is generating a separate report on MMC. It is a national consortium created by MITI (Ministry of International Trade and Industry) through NEDO (New Energy and Industrial Technology Development Organization). So far, it has 27 member companies, three of which are of foreign origin. There are two member companies from the US (IS Robotics, Inc. and SRI International) participating in MMC's activities. MMC is an administrative unit and no research is conducted in house. Total of 25 bil yen has been committed for 10 years starting 1991, and the research funds are distributed to different member companies to carry out specific research topics related to micromachines. Organizations interested in finding out about their activities should look for official solicitations through JETRO (MITI published) or at MEMS conferences.
- Meeting was held with the managing director, Mr. Tsunemi, Dr. D. Kahaner, and Dr. Paul Ro, with other managers from MMC.

Wed

- Discussion with Prof. Higuchi at KAST; a picture taking session; a meeting with Dr. J. Jin, a former Ph.D. student of Prof. Higuchi, who is a full-time researcher at KAST
- Prof. Higuchi showed around the lab, and oversaw the picture taking session personally. There were some sensitive research activities going on at KAST that he did not want to expose at this point. Pictures of experimental setups for film actuators and active MB based robot wrist were taken.
- Meeting with Dr. Jin was on the topic of electrostatic levitation device for silicon wafer. The project is just starting out and there are some stability problems with the device at this point. It uses 700V source with aluminum based electrodes.
- Dr. Jin also discussed about his Ph.D. topic, which is Magnetic levitation using tuned LC circuit. Some papers were collected to this end.

Thur

- Mr. Oka's magnetic levitation using permanent magnet was studied. A few papers are collected toward this topic. The main advantage comes from the omission of electromagnet which generates heat and wastes energy. A simple linear feedback control of a prototype system proved to be effective with positioning accuracy of 1micron. The prototype consisted of a levitating steel ball under which is a gap sensor, PM supported by a compliant set of spring steel beams, and a voice coil that controls the vertical motion of the PM. Mr. Oka is concentrating on a coaxial gap sensor measurement and DSP based control of the levitation.

Fri

- Met with Dr. Kahaner to visit Yaskawa Electric, Inc. and Mechanical Engineering Lab at Tsukuba City
- Mr. Kanabe was in charge of hosting us at Yaskawa. Many interesting projects were shown including flagellar motors (world's smallest biological motors), micro-manipulator maintenance system for power plants (part of MicroMachine Center projects), and two arm robot assembly system
- Mr. Maegawa was in charge of hosting us at Mechanical Engineering Lab. First, an introductory video overview was given, followed by a tour of three laboratories. The first lab visited has worked on precision torque control of a DC motor through a sensory

feedback and adaptive control. A confidential work on two arm micro manipulation is currently going on.

An interesting micro gripper work was shown in the second lab. The third lab was carrying out research in robotic hand and related sensing technology including tactile sensor that utilizes fiber optics and totally internally reflecting properties of white light source. (A brief report is written on this visit.)

Week 5 (6/21 - 6/25)

Mon

- Visited Canon Inc. at Shimomaru. Mr. M. Negishi hosted the visit and arranged to have presentations and a tour of their super smooth polishing set-up. In the seminar, Dr. Ro presented a talk on two control related topics followed by two presentations on super smooth polishing. Related papers on this topic has been collected.

Tue - Thur

- Final wrap-up, report writing, paper collection, and picture taking. Pictures are taken of Mr. Liu's thesis is dealing with impact drive system for impact type writer head. NEC has developed a clever system that amplifies the motion of the PST stack through a kinematic linkage system. This particular link mechanism amplifies the range of motion by a factor of 20 to 300 microns. Also, Mr. Song's work on applying another type of impact drive for laser disk centering was taken.

Fri

- Dropped off a bundle of papers and proceedings to Dr. David Kahaner's office for shipment. Final preparation and present shopping spree.